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Ultrathin quartz plate-based multilayer MoS_2 for passively mode-locked fiber lasers (invited)

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ABSTRACT

We have grown ultrathin quartz plate-based multilayer molybdenum disulfide (MoS_2) by chemical vapor deposition (CVD). When employed as saturable absorber (SA), the prepared MoS_2 device exhibits remarkable merits (e.g. uniform thickness, high quality of crystal lattice high damage threshold easy fabrication and good practicability). The modulation depth, saturable intensity, and non-saturable loss of this SA device are measured to be 16.1%, 0.438 MW/cm^2 and 44.6% respectively. By incorporating the SA into a typical ring cavity erbium-doped fiber laser, stable passive soliton mode-locked pulse is achieved with the repetition frequency of 0.987 MHz, the signal noise ratio (SNR) of 71.4 dB and the pulse duration of 2.17 ps. The experimental results demonstrate our MoS_2-SA device to be an effective mode locker, and it is promising to be used in ultrafast photonics.

1. Introduction

Ultrafast fiber lasers have attracted considerable interests due to their various practical applications in optical communication, biomedical imaging, frequency metrology and materials processing [1,2]. Compared to the active mode-locking scheme, the passive mode-locking scheme has the merits of compactness, simplicity and low cost. In the last two decades, nonlinear optical loop mirror (NOLM), nonlinear polarization rotation (NPR) were the widely-used passive mode-locking schemes for ultrashort pulse generation. However, they are extremely sensitive to the environmental fluctuation, which limits their practical applications. By simply incorporating a real saturable absorber (SA), the laser performance of environmental stability would be enhanced distinctly as has been proved by semiconductor saturable absorption mirrors (SESAMs). To date, SESAMs almost remain to be dominate devices employed in commercial solid-state pulsed lasers. But SESAMs usually suffer from such drawbacks as expensive price, complicated fabrication and packaging, narrow operation waveband (few tens of nanometers) as well as limited response time (few picoseconds). As a result, there are always great motivations for researches to explore alternative SA materials with better nonlinear optical properties and feasible photonic devices with merits of low cost and easy fabrication.

Low-dimensional materials with outstanding optical properties are catching increasingly worldwide attentions in the field of ultrafast photonics. They are widely implemented in passively mode locked fiber laser systems [3–5], such as carbon nanotubes (CNTs) [6–10], graphene [11–19], topological insulators (TIs) [20–28], transition metal dichalcogenides (TMDs) (e.g. MoS_2 [29–35], tungsten sulfide (WS_2) [36–43], molybdenum selenide ($MoSe_2$) [44–46] and tungsten selenide (WSe_2) [47,48]) and recently discovered black phosphorus (BP, also known as phosphorene) [49–53]. By employing these SAs, stable optical pulses from picosecond to femtosecond region have been achieved in different fiber laser systems. Among all of the SAs, graphene is one of the most studied nanomaterial after the first exfoliation from bulk graphite. As a zero-bandgap crystal with Dirac-like electronic band structure, graphene has been applied to wideband optical modulators and mode-locked fiber lasers [11–19]. However, when graphene is used as a SA device, it has such inherent defect as weak modulation depth of ~1.3% and low optical absorption efficiency of 2.3% [11,15], which lowers its ability for self-starting mode-locking. TIs (i.e., Bi_2Te_3 and Bi_2Se_3), as one group of quasi-2D materials, are proved with a gapless metallic surface state and an insulating bulk state with limited bandgap (0.2–0.3 eV). But their indirect bandgap and relatively long intraband relaxation time (~0.5 ps) also limit their optoelectronic applications as an efficient and fast modulator for stabilizing femtosecond laser [54].

In comparison, layered TMDs possess many relatively remarkable optoelectronic properties, such as indirect-to-direct bandgap transition with reducing number of layers, high carrier mobility

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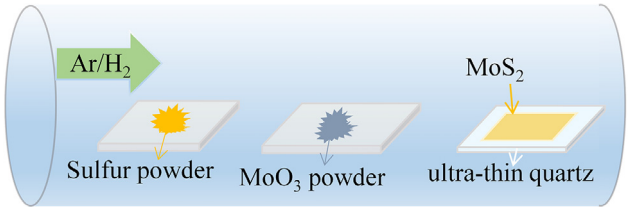

Fig. 1. Schematic of the growth of ultrathin quartz-based MoS_2 by CVD method.

(~140 cm^2 V^{-1} s^{-1}), and high third-order nonlinear susceptibility (Im $\chi^3 \sim 10^{-8}$) [55,60], enabling the family of TMDs more competitive as SAs in ultrafast fiber lasers. Most recently, BPs have been reported as a kind of direct bandgap semiconductor from monolayer to few layers whose bandgap can be controlled by altering number of layers. In 2015, Zhang et al. firstly demonstrated passively mode-locked and Q-switched fiber laser based on BP nanosheets or quantum dots in the near region of 1550 nm [56]. Consequently, the preparation of effective SAs with higher crystal quality and better performance becomes a key step for ultrafast fiber lasers.

Various methods have been developed to fabricate 2D materials. Generally, the fabrication techniques can be mainly divided into two catalogues: top-down exfoliation and bottom-up growth. The former involves cleaving layered nanomaterials from bulk crystal, such as mechanical exfoliation (ME) [56,57] by the adhesive tape, liquid-phase exfoliation (LPE) [58,59] through dispersal in solvents. However, either ME or LPE method could not accurately control the thickness/size of the generated flakes. Alternatively, the latter includes the well-known (CVD) method [60,61], magnetron sputtering deposition (MSD) method [62,63] and pulsed laser deposition (PLD) method [64,65]. These methods could grow high-quality thin film directly on the substrate with uniform thickness and crystallization state, thus overcoming the defects of both ME and LPE. To prepare SA devices, a variety of strategies can be employed based on the 2D materials. For example, graphene or layered TMDs can be hosted into PVA and transferred to the tip of a pigtail or directly deposited on fiber ferrules to develop practical mode lockers [66–68]. Alternatively, the TMDs nanosheets can be deposited on microfibers [69–72] or side-polished (D-shipped) fibers [73,74] or embedded into the air channels of photonic crystal fiber (PCF) [75–78] to form unique devices for mode-locking. However, these evanescent-wave-based SA devices are frangible and need to be packaged for practical applications, thus making their fabrication procedure very complicated.

In this paper, we proposed a simple scheme for the preparation of SA devices by directly growing MoS_2 film on ultrathin quartz plate by CVD method. The MoS_2 covered quartz plate was measured with a good transmittance of ~87% at 1563 nm. It can be feasibly divided into small pieces with size of ~1 mm×1 mm and directly sandwiched between fiber ferrules. By employing the SA device in an erbium-doped fiber ring-cavity, we achieved stable passive mode-locking operation with pulse duration of 2.17 ps, and SNR of 71.4 dB. The new approach for the fabrication of SAs was experimentally demonstrated very effective for self-starting mode locking operation.

2. Fabrication and characterization of MoS_2-SA

For the CVD-grown 2D material film, it is a challenge to transfer it from the substrate to the fiber ferrule surface [60]. Besides, the crystal lattice structures of the film are usually damaged during this transfer process. To overcome this disadvantage, we propose a novel scheme to fabricate the SA device. In the first step, the MoS_2 film is directly grown on an ultrathin quartz plate with thickness of 134 μm, as briefly depicted in Fig. 1. 500 mg of MoO_3 powder was placed in the center of the furnace and 500 mg of sulfur powder was placed at the upstream. Several pieces of ultrathin quartz plate were used as substrates and placed downstream. The chamber was evacuated to a base pressure of 0.1 T, and then flowed with Ar gas, which was controlled by a mass flow controller. After the pressure stabilized, the furnace was heated to 550 °C at a rate of 25 °C/min and maintained for 30 min. The sulfur powder was heated by a twisted heating belt with the temperature of

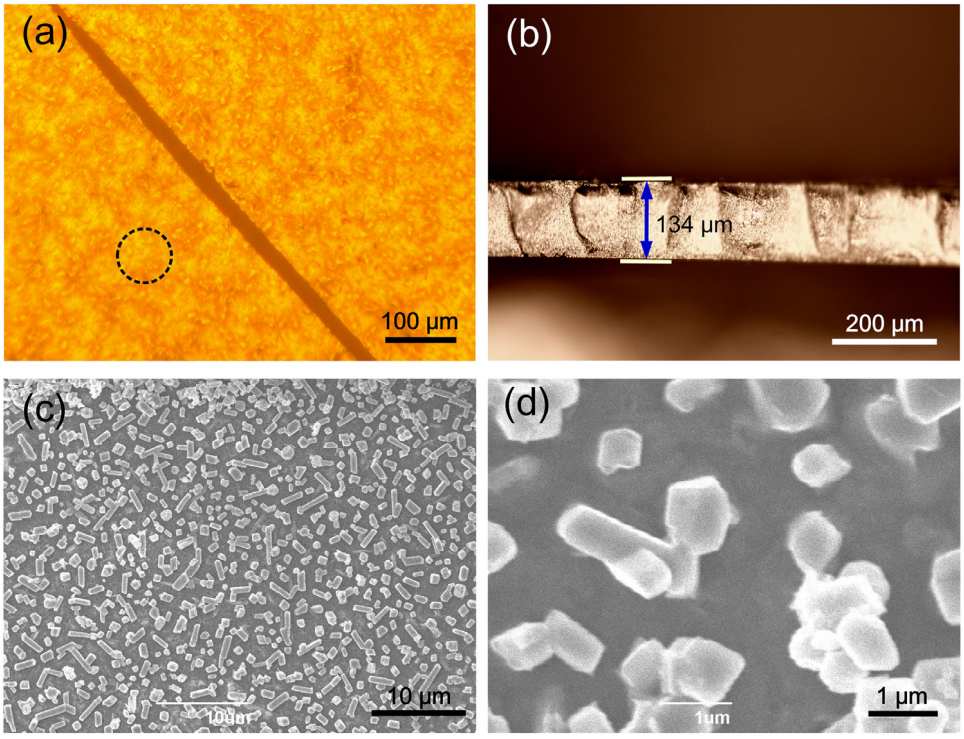

Fig. 2. Morphology of the MoS_2 film on ultrathin quartz plate. (a) The surface optical image. (b) The side view image. (c) and (d) SEM images with different resolution.

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